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Are Messages of R-parity Violating Supersymmetry Hidden within Top Quark Signals ?

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Abstract

In an R-parity nonconserving supersymmetric theory, the lighter stop can dominantly decay into $b\mu$ and $b\tau$ if R-parity breaking has to explain the neutrino mass and mixing pattern suggested by the data on atmospheric muon neutrinos. This should give rise to $dilepton + dijet$ and $single - lepton + jets$, signals identical with those of the top quark at the Fermilab Tevatron. One can thus constrain the stop parameter space using the current top search data, and similarly look for the first signals of supersymmetry at the upgraded runs of the Tevatron.

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It has been repeatedly suggested that in a supersymmetric (SUSY) scenario [1], one of the two spin-zero superpartners of the top quark, popularly known as stop, could be considerably lighter than any other strongly interacting superparticle [2]. This happens due to the mixing between the left-and right chiral stops, which can be quite large in principle, reducing the mass of the lighter eigenstate. Also, negative contribution from Yukawa coupling in the evolution equations for scalar mass parameters can cause the stop to be lighter than the other squarks in a framework where all squark flavours have the same mass at a high energy scale. It has been shown that in the minimal supersymmetric standard model (MSSM), a light stop ($\tilde{t}_1$) will decay dominantly through the channels $\tilde{t}_1 \rightarrow c\chi_1^0$ and $\tilde{t}_1 \rightarrow b\chi_1^+$, where χ_1^0 and χ_1^+ are the lightest neutralino and the lighter chargino respectively. Out of these, the former reigns supreme [3] if the light stop is even lighter than χ_1^+ [4]. Based on the ensuing signals, experiments at the Fermilab Tevatron have set a lower limit of about $120 - 135$ GeV on the lighter stop [5] depending on the mass of the lightest neutralino.

The observed signals can be quite different when R-parity, defined as $(-1)^{3B+L+2S}$, is not a conserved quantity, something that is both theoretically and phenomenologically consistent in supersymmetric theories so long as only *one* of baryon number (B) and lepton number (L) is violated. In such cases, the lightest supersymmetric particle (LSP) can be unstable, thereby altering the signals of SUSY [6,7]. If, in addition, the LSP (which is the lightest neutralino in most theories) is massive enough to evade searches at the large electron-positron collider (LEP), then the observation of SUSY at the Fermilab Tevatron may depend squarely on the production and decays of the light stop for whom R-parity violation opens up new and often dominant decay modes. The limits based on $\tilde{t}_1 \rightarrow c\chi_1^0$ require re-examination in such a case.

In this letter, we want to point out that the easiest identifiable signatures of a light stop (and therefore perhaps of SUSY itself) in an R-parity nonconserving framework could be in final states that have been, and still are, widely studied to look for the *top quark* at the Tevatron, namely, the *dimuon+dijet* as well as *single muon+jets* signals. We further argue that stop decays leading to such final states are imperative in R-parity violating scenarios that lead to neutrino masses and mixing as required by the recent SuperKamiokande (SK) data on atmospheric muon neutrinos. Thus a careful reanalysis of the already existing Tevatron Run I results on top search may allow us to explore a large region of the light stop parameter space of such theories, where the search channel employed for MSSM is not going to be effective. In Run II one can have an even wider prospect, not only for constraining the SUSY parameter space but also for the possibility of top signals being actually faked by the stop. In addition, some new signals for such models, very similar to those of the top quark, are suggested here.

Expressed in terms of the quark, lepton and Higgs superfields, the MSSM superpotential is

$$W_{MSSM} = \mu \hat{H}_1 \hat{H}_2 + h^l_{ij} \hat{L}_i \hat{H}_1 \hat{E}^c_j + h^d_{ij} \hat{Q}_i \hat{H}_1 \hat{D}^c_j + h^u_{ij} \hat{Q}_i \hat{H}_2 \hat{U}^c_j \tag{1}$$

where μ is the Higgsino mass parameter and the last three terms give all the Yukawa interactions.

The possible additions to this superpotential due to R-parity violation (through lepton number violation only) are given by [6]

$$W_{\not{L}} = \epsilon_i \hat{L}_i \hat{H}_2 + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}^c_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}^c_k \tag{2}$$

We consider only the effects of the trilinear additional terms in the superpotential; we shall point out at the end of the paper that the effects we are suggesting can arise also from the bilinear terms $\epsilon_i \hat{L}_i \hat{H}_2$.

If the SK data [8] on atmospheric muon neutrinos (and also similar data from the Soudan-II [9] and MACRO [10] experiments) have to be explained in terms of $\nu_\mu - \nu_\tau$ oscillations, then the mass-squared splitting between the second and third lightest physical neutrino states will have to be $\Delta m^2_{23} \simeq 5 \times 10^{-3}$, in addition to near-maximal mixing between the corresponding flavour eigenstates. R-parity violation in the form of the λ-and λ'-type interactions in equation 2 can give rise to neutrino mass terms at one-loop level, the generic expression for them (in the flavour basis) being

$$
\begin{aligned}
(m_\nu^{\rm loop})_{ij} \simeq & \frac{3}{8\pi^2} m_k^d m_p^d M_{SUSY} \frac{1}{m_{\tilde{q}}^2} \lambda'_{ikp} \lambda'_{jpk} \\
& + \frac{1}{8\pi^2} m_k^l m_p^l M_{SUSY} \frac{1}{m_{\tilde{l}}^2} \lambda_{ikp} \lambda_{jpk}
\end{aligned} \tag{3}
$$

where $m^{d(l)}$ denote the down-type quark (charged lepton) masses. $m_{\tilde{l}}^2$, $m_{\tilde{q}}^2$ are the slepton and squark mass squared. $M_{SUSY}(\sim \mu)$ is the effective scale of supersymmetry breaking. The mass and mixing patterns suggested by the observed ν_μ data can be accommodated in the above scheme of mass generation if $\lambda'_{233} \simeq \lambda'_{333} \simeq$ *a few times* 10^{-4} [11]. An immediate consequence of such couplings is the decay of the lighter stop in the channels $\tilde{t}_1 \rightarrow b\tau^+$ and $\tilde{t}_1 \rightarrow b\mu^+$ with comparable widths.

There is a considerably large region of the parameter space, not yet constrained by any experimental data, where the stop is the second lightest supersymmetric particle next to the lightest neutralino. In this region, the three lowest-order decay channels available to the stop are $\tilde{t}_1 \rightarrow c\chi_1^0$, $\tilde{t}_1 \rightarrow b\tau^+$ and $\tilde{t}_1 \rightarrow b\mu^+$ [12]. The first one, a well-studied process, is a consequence of neutral flavour violation in SUSY and is suppressed by the small mismatch between quark and squark mass matrices. The latter ones are driven by λ'_{233} and λ'_{333}, and we find that they dominate for a light stop with mass ≤ 150 GeV so long as $\lambda'_{233}, \lambda'_{333}$ lie in the range specified above, in conformity with the SK data.

We focus our attention on single-muon and dimuon final states, together with jets and missing energy, arising from (light) stops pair-produced in $p\bar{p}$ collisions at the Fermilab Tevatron, with either both decaying into $b\tau$ or one of them into $b\tau$ while the other goes to $b\mu$. The same final states have been extensively analysed for the determination of the mass and production cross-section of the top quark. It should be noted that the τ produced together with a b quark in the two-body decay of a stop (with mass $100 - 150$ GeV) can have sufficient p_T for the resulting jets/muons/neutrinos to often pass the p_T or $\not{E}_T$ cuts associated with the top quark signals. Thus, depending upon whether the tau decays hadronically or semileptonically, the stop decays can contribute to top-like signals of the form (i) *single muon* $+ 3jets + \not{E}_T$ and (ii) *dimuon* $+ 2jets + \not{E}_T$, provided that the jets/leptons satisfy the requisite cuts.

We present some numerical estimates where the five degenerate squark flavours are assumed to have masses $\approx$ 400 GeV. The mass of the lighter stop is made to vary beween 80 and 150 GeV, while the $SU(2)$ gaugino mass M_2 is held fixed at 150 GeV. Unification of the gaugino masses has been assumed. In addition, $\tan\beta$, the ratio of the two Higgs expectation values, has been fixed at 3. Although we have *not* assumed any definite high scale SUSY breaking mechanism, it can be verified that such combinations of parameters can indeed be realised in a supergravity (SUSY) framework. This is possible by using one's freedom [13] with the trilinear soft SUSY breaking term A (while still preserving charge and colour invariance [14]) and using the Higgsino parameter μ as a phenomenological input [15], something that is justfied if the Higgs mass parameters retain the freedom of differing from the 'universal' sfermion mass parameter (m_0).

The above specified set of parameters allows one to calculate the R-conserving stop decay width. For the R-parity violating two-body decays, we have used three sets of values for $\lambda'_{233} = \lambda'_{333}$, consistent with the expectation from the SK results. Using these, it is straightforward to calculate the branching ratios of the various stop decay modes. It is found that for the region of parameter space under investigation here, the branching ratio for R-parity violating decays ranges from 75 to 99 per cent, with a near-equal share between the $b\tau$ and $b\mu$ channels.

A parton level Monte Carlo calculation has been performed for both *single muon + three jets+* $\not{E}_T$ and *dimuon + two jets+* $\not{E}_T$ final states arising from stop pair-production at the Tevatron. In the former case, we have demanded that at least one jet be identified as a b-induced one. Both the top- and stop-production cross-sections have been QCD corrected using a a so-called K-factor of 1.4 in case of top [16] and 1.3 [17] for the stop. For hadronic decays of the tau, we have considered only modes with one charged track, arising from $\tau^\pm \to \pi^\pm\nu_\tau,\ \rho^\pm\nu_\tau,\ a_1^\pm\nu_\tau$. In order to calibrate our parton-level results, we have computed the numbers of the same types of expected signal events from top quark pair production. The numbers of both single-muon and dimuon events thus calculated in the latter case agree, within small errors, with the actual observations [18,19], so that our results may be treated as reasonable estimates of how many stop-induced events can be contained in the top signal.

Since our main purpose is to see how stop signal can percolate into top signals for which detectors are already designed, both have been subjected to the same set of cuts, as specified by the CDF top search strategy. In both types of final states of our interest, jets are defined using the cone algorithm as discussed in Ref. [18,19]. Jets are counted in the analysis only if $|\eta|_{jet} < 2$ where η is the pseudorapidity [18,19]. For single muon final state we require jets with $E_T > 15$ GeV, at least one of which is identified as a b-jet (with identification efficiency ≈ 40 % [18]) while for dimuon final state two jets with $E_T > 10$ GeV are required [19]. Two jets are merged if $\Delta R \leq 0.4$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, $\Delta\eta$ and $\Delta\phi$ being the separations in pseudorapidity and azimuthal angle. In both the cases *isolated* muon(s) with $p_T > 20$ GeV are necessary in the central region with $|\eta| < 1$ [18,19]. The criterion for muon isolation imposed here is that the total E_T within a cone of $\Delta R = 0.4$ around it should be less than 10 % of its own p_T. In dimuon final states, backgrounds from real Z are rejected by requiring the dimuon invariant mass to be outside the interval $75 - 105$ GeV [19]. For single muon events, missing transverse energy, $\not{E}_T > 20$ GeV is demanded [18] while for dimuons $\not{E}_T > 25$ GeV is generally required [19]. It is observed in the last of Ref. [19] that this combination of cuts effectively eliminates backgrounds from Drell-Yan production and other relevant processes for the dimuon final state.

The net contribution of the stop to the top-like signals depends on two effects: the production cross section of a stop pair vs that of a top pair, and the relatively large branching fraction for the stops cascading into the final states of our interest. In addition, of course, the susceptibility to cuts plays a role. For $m_{\tilde{t}_1} \approx 100$ GeV the production rates approximately match, and the stop production rate falls for higher stop masses.

Figures 1 and 2 contain our main results, based on an integrated luminosity of 109 pb^{-1}. We have checked by varying the parameter μ between -700 and $+700$ GeV that the results are not altered by more than about 25 per cent. The dimuon events enable us to rule out a slightly larger range of the stop mass. This is because of more suppression of the top signal in this channel through leptonic branching fractions of W as opposed to what happens for stop-pairs. It is clear from figure 2 that the dimuon data should definitely rule out the entire stop mass interval that is otherwise constrained assuming $B(\tilde{t}_1 \to c\chi_1^0) \simeq 1$. In fact, the limit can perhaps be pushed somewhat higher up in the R-parity violating case. For $\lambda'_{233} \simeq \lambda'_{333} = 10^{-4}$, this limit should be around 125 GeV with the currently available data, while for λ'-values of 5×10^{-4} it touches about 140 GeV.

From the single muon signal too, stop masses upto about $120 - 125$ GeV seem to be ruled out. We also want to emphasize that both this channel and the dimuon one can be used effectively in the context of Run II of the Tevatron to look for SUSY signals burried within the top data. A careful analysis of the dimuon versus dielectron data there, invigorated by the additional available luminosity, may lead to successful identification of an excess in the former, thereby indicating R-parity violation of a kind that simultaneously explains the atmospheric neutrino puzzle.

For simplicity, we have confined ourselves in the above discussion to cases where the stop is kinematically forbidden to decay into a b quark and a chargino. Such a decay can be possible when M_2 and consequently the mass of lightest neutralino is smaller. However, in view of the fact that the chargino can subsequently decay into a lepton, the above mode can in effect strengthen the stop contribution.

Another signal, similar in nature to the ones discussed above, is one where both the stops decay into the $b\mu$ channel. In this case one shall see dimuons with two jets. Proper b-identifaction in the jets, together with effective measures to eliminate the Drell-Yan backgrounds, can establish such final states as rather effective ones for discovering a light stop in an R-parity violating theory.

As has been mentioned at the beginning, the above discussion has assumed only trilinear R-parity violating interactions. The presence of the bilinear terms of the form $L_i H_2$ in the superpotential (and the consequent vacuum expectation values for sneutrinos) can give rise to mixing between charged leptons and charginos [20], which can again lead to top-like signals of the same kinds from stop decays. A detailed analysis of the signals in such a case will soon be presented by us [21].

In conclusion, the first signals of R-parity violating SUSY observable in current and upcoming experiments can very well mimic those of the top quark. This is particularly true if the theory has to account for the neutrino masses and mixing suggested by experimental results on atmospheric muon neutrinos. We can use the already available *single lepton+jets* as well as *dilepton* data from the Fermilab Tevatron to constrain a large range of the lighter stop mass in such a scenario. In the upgraded version of the Tevatron, too, top quark signals will continue to be useful probes for such types of SUSY.

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FIGURES

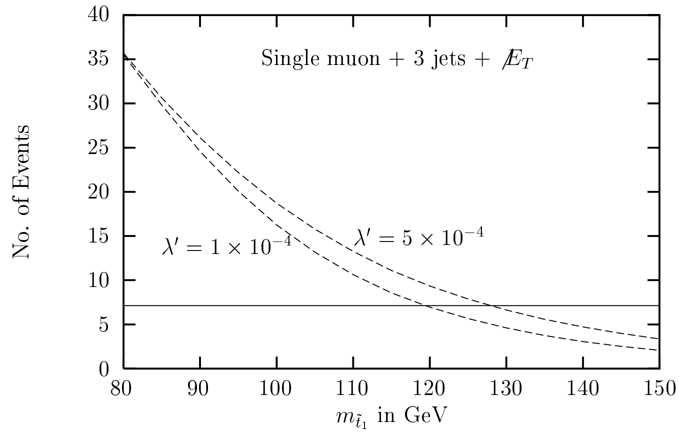

FIG. 1. Contributions to single muon + 3 jets + $\not{E}_T$ events from $t\bar{t}$ production for $m_t = 175$ GeV (solid line) and $\tilde{t}_1\tilde{t}_1^*$ production (followed by R-parity violating decays of $\tilde{t}_1$'s, dashed lines) as a function of $m_{\tilde{t}_1}$ at Tevatron with $\sqrt{s} = 1.8$ TeV and an integrated luminosity of 109 pb^{-1} and using the same set of cuts (see text). The MSSM parameters used are : $M_2 = 150$ GeV, $\mu = \; - 400$ GeV, $\tan\beta = 3$, $\theta_{\tilde{t}}$(stop mixing angle) $\approx -45°$, $m_{Q,U,D} = 400$ GeV for first two generations of squarks. We take $\lambda' = \lambda'_{233} = \lambda'_{333}$. CTEQ-4M parton distributions are used.

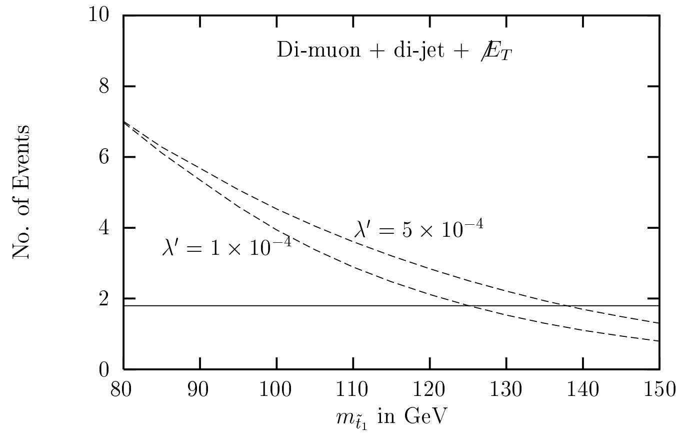

FIG. 2. Same as in Fig. 1 except for contributions to di-muon + di-jet + $\not\!\!E_T$ events.